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Gamma ray generation by interactions of flare energetic particles with stellar wind matter

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Abstract. For different types of local stars with flare activity we calculate expected gamma-ray fluxes in periods of flare energetic particle (FEP) generation. We suppose that main processes of FEP generation and propagation in the stellar-sphere are similar with processes in the Heliosphere but with much bigger energetic. We calculate the space-time-energy distribution of these particles in the stellar-sphere in the periods of FEP events. On the basis of investigations of cosmic ray nonlinear processes we determine the space-time distribution of stellar wind matter. Then we calculate the generation of gamma rays by decay of neutral pions generated in nuclear interactions of FEP with stellar wind matter and determine the expected space-time distribution of gamma-ray emissivity. Then we calculate the expected time variation of the angle distribution and spectra of gamma ray fluxes. For some simple diffusion models of stellar FEP propagation we obtain analytical approximation described the time evolution of gamma ray flux angle distribution as well as time evolution of gamma ray spectrum. It is shown that by observations from local stars of gamma rays generated by stellar FEP interactions with stellar wind matter can be obtain important information on stellar activity, on FEP spectrum, on mode of FEP propagation, and on matter distribution in the inner stellar-sphere.

1 Introduction

The generation of gamma rays (GR) by interaction of flare energetic particles (FEP) with stellar wind matter shortly was considered in Dorman (1996, 1997). Here we will give a development of this research with much more details. GR generation in the stellar wind by FEP from stellar flares is determined mainly by 3 factors:

1st- by space-time distribution of stellar FEP in the stellar-sphere, their energetic spectrum and chemical composition; for this distribution can be important nonlinear collective effects (especially for great events) of FEP pressure and kinetic stream instability (see in Berezinskii et al., 1990; Dorman, 1995).

2nd- by the stellar wind matter distribution in space and its change during stellar activity cycle; for this distribution will be important also pressure and kinetic stream instability of galactic cosmic rays as well as of stellar FEP, especially in periods of very great events (Dorman et al., 1990; Zirakashvili et al., 1991; Le Roux and Fichtner, 1997).

3rd- by properties of stellar FEP interaction with stellar wind matter accompanied with GR generation through decay of neutral pions (Stecker, 1971; Dermer, 1986a,b).

After consideration of these 3 factors we will calculate expected GR emissivity space-time distribution, and expected fluxes of GR on the distance 1 AU from the star in dependence of time after FEP ejection into stellar wind for different directions. We calculate expected fluxes also for different distances from the star inside the stellar-sphere and outside. It is important, that in some types of stars the total energy in FEP is several orders higher than in solar flares and lost matter speed is several orders higher than from the Sun (Gershberg and Shakhovskaya, 1983; Korotin and Krasnobaev, 1985; Gershberg et al., 1987; Kurochka, 1987). It will be shown that future observations of GR generated in interactions of stellar FEP with stellar wind matter can give important, unique information on total energy and energetic spectrum of stellar FEP, on mode of its propagation as well as information on stellar wind matter distribution and stellar coronal activity.

2. The 1st Factor: Stellar FEP Space-Time Distribution

2.1. Model of stellar FEP propagation

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In the first approximation the time change of stellar FEP and energy spectrum change can be described by the solution of isotropic diffusion (characterized by the diffusion coefficient $D_i(E_k)$) from pointing instantaneous source $Q_i(E_k,\mathbf{r},t)=N_{oi}\delta(\mathbf{r})\delta(t)$ of stellar FEP of type *i* (protons, α – particles and heavier particles, electrons) by

$$N_i(E_k,\mathbf{r},t)=N_{oi}(E_k)\times \left[2\pi^{1/2}(D_i(E_k)t)^{3/2}\right]^{-1}\exp\left(-\mathbf{r}^2/(4D_i(E_k)t)\right), \tag{1}$$

where $N_{oi}(E_k)$ is the energetic spectrum of total number of solar FEP in the source. At the distance $r=r_1=1AU$ the maximum of stellar FEP density

$$N_{i\,max}(r_1,E_k)/N_{oi}(E_k)= 2^{1/2}3^{3/2}\boldsymbol{\pi}^{-1/2}\,exp(-3/2)\,r_1^{-3}=0.925\,r_1^{-3} \tag{2}$$

will be reach according to Eq. (1) at the moment

$$t_m(r_1,E_k)=r_1^2\big/6D(E_k), \tag{3}$$

and the space distribution of stellar FEP density at this moment will be

$$N_i(r,E_k,t_m)/N_{oi}(E_k)= (54/\boldsymbol{\pi})^{1/2}\,r_1^{-3}\,exp\left(-3r^2\big/2r_1^2\right). \tag{4}$$

2.2. Energy spectrum of stellar FEP in the source

The energetic spectrum of generated stellar energetic particles in the source approximately can be described as

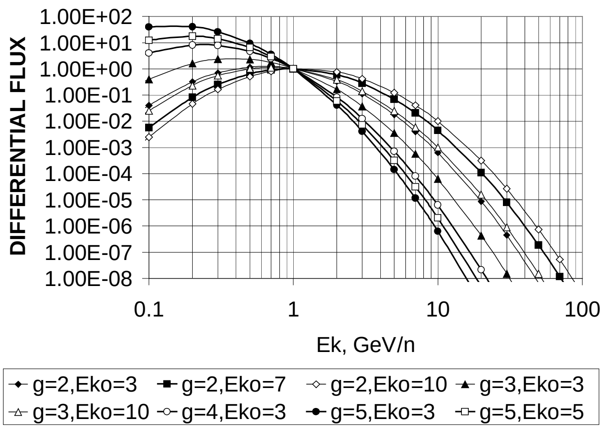

Fig.1. Expected energy spectrums in stellar FEP sources

$$N_{oi}(E_k)\approx N_{oi}E_k^{-\boldsymbol{\gamma}}, \tag{5}$$

where γ increases with increasing of energy: for example, for solar FEP for great event February 23, 1956 it increases from about 0÷1 at $E_k\le 1$ *GeV/nucleon* to about 6÷7 at $E_k\approx 10\div 15$ *GeV/nucleon.* Approximately the behavior of value γ in Eq. (5) can be described as

$$\gamma=\gamma_o+\ln(E_k/E_{ko}), \tag{6}$$

where parameters γ_o and E_{ko} can be different for individual events (for solar FEP mainly $2\le\gamma_o\le 5$ and $2\le E_{ko}\le 10$ *GeV/nucleon*; we suppose that about the same situation will be for stellar FEP). Fig. 1 shows spectrums of stellar FEP in source at different values of parameters γ_o and E_{ko}. The position of maximum in Eq. (5) with taking into account Eq. (6) is determined by

$$E_{k\,\max}=E_{ko}\exp(-\gamma_o)\ . \tag{7}$$

2.3. The total energy of stellar FEP

The total energy contained in FEP will be according to Eq. (5)-(7):

$$E_{tot}=N_{oi}\int_0^\infty E_k^{1-\boldsymbol{\gamma}_o-ln(E_k/E_{ko})}dE_k=N_{oi}\boldsymbol{\Psi}(\boldsymbol{\gamma}_o,E_{ko}) \tag{8}$$

where

$$\boldsymbol{\Psi}(\boldsymbol{\gamma}_o,E_{ko})=\int_{-\infty}^{\infty}E_{ko}^{2-\boldsymbol{\gamma}_o-x}\,exp\left(-x^2+2x-\boldsymbol{\gamma}_o\right)dx \tag{9}$$

what can be approximated by

$$\boldsymbol{\Psi}(\boldsymbol{\gamma}_o,E_{ko})=A_o(E_{ko})+A_1(E_{ko})\boldsymbol{\gamma}+ A_2(E_{ko})\boldsymbol{\gamma}^2+A_3(E_{ko})\boldsymbol{\gamma}^3\ . \tag{10}$$

Coefficients $A_i(E_{ko})$ are shown in Table 1.

Table 1. Coefficients $A_i(E_{ko})$ in Eq. (10).

E_{ko} *GeV/n*	$A_3(E_{ko})$	$A_2(E_{ko})$	$A_1(E_{ko})$	$A_o(E_{ko})$
3	0.1325	-0.2874	-0.6850	3.2367
5	-0.1498	1.8526	-6.8603	9.7251
7	-0.0337	0.8713	-3.8203	6.3696
10	-0.3306	3.5171	-12.200	15.685

For great stellar FEP events $E_{tot}\approx 10^{35}\div 10^{37}$ *erg* [19-22] what is several orders bigger than in solar FEP (for great solar FEP events $E_{tot}\approx 10^{31}\div 10^{32}$ *erg*).

3. 2nd-Factor: Space-Time Distribution of Stellar Wind Matter

If we assume for the first approximation the model of Parker (1963) of radial stellar wind expanding into the stellar-sphere (which is in a good accordance with experimental data for solar wind) then the behavior of matter density of stellar wind will be described by the relation

$$n(r,\theta)=n_1(\theta)u_1(\theta)r_1^2\big/\left(r^2u(r,\theta)\right), \tag{11}$$

where $n_1(\theta)$ and $u_1(\theta)$ are the matter density and stellar wind speed at the latitude θ on the distance $r=r_1$ from star $(r_1=1AU)$. The dependence $u(r,\theta)$ is determined by the interaction of stellar wind with galactic cosmic rays, with interstellar matter and interstellar magnetic field, by interaction with neutral atoms penetrating from interstellar space inside the stellar-sphere, by the nonlinear processes caused by these interactions (Dorman, 1995; Le Roux & Fichtner, 1997). We suppose that the dependence of $u(r,\theta)$ from *r* caused by these nonlinear processes can be described by the same relation as what obtained for solar wind:

$$u(r) \approx u_1(\theta)(1 - b(r/r_o)), \tag{12}$$

where r_o is the distance to the terminal shock wave (what determined mainly by the equilibrium between dynamical pressure of stellar wind and the sum of galactic CR pressure, pressure of galactic magnetic field and by processes of neutral atoms penetrating from interstellar space inside the stellar-sphere), and parameter *b* depends from sub-shock compression ratio (for solar wind according to Le Roux & Fichtner (1997) this parameter is in interval $0.13 \le b \le 0.45$; for stellar winds we will use some average value *b*=0.3).

4. 3-rd factor: GR generation by FEP in the stellar-sphere

4.1. Generation of neutral pions in the stellar-sphere

According to Stecker (1971), Dermer (1986a,b) the neutral pion generation caused by nuclear interactions of energetic protons with hydrogen atoms through reaction $p + p \to \pi^o +$ anything will be determined by

$$F_{pH}^{\pi}(E_\pi, r, \theta, t) = 4\pi n(r,\theta,t) \int_{E_{k\,\min}(E_\pi)}^{\infty} dE_k \times N_p(E_k, r, t)\langle\varsigma\sigma_\pi(E_k)\rangle(dN(E_k, E_\pi)/dE_\pi), \tag{13}$$

where $n(r,\theta,t)$ is the density of stellar wind, determined by Eq. (11), $E_{k\,\min}(E_\pi)$ is the threshold energy for pion generation, $N_p(E_k, r, t)$ is stellar FEP density determined by Eq. (1), $\langle\varsigma\sigma_\pi(E_k)\rangle$ is the inclusive cross section for reactions $p + p \to \pi^o +$ anything, and

$$\int_0^{\infty} (dN(E_k, E_\pi)/dE_\pi) dE_\pi = 1 . \tag{14}$$

4.2. Space-time distribution of GR emissivity

GR emissivity caused by nuclear interactions of FEP protons with solar wind matter will be determined according to Stecker (1971), Dermer (1986a,b) by

$$F_{pH}^{\gamma}(E_\gamma, r, \theta, t) = 2 \int_{E_{\pi\,\min}(E_\gamma)}^{\infty} dE_\pi \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} F_{pH}^{\pi}(E_\pi, r, \theta, t), \tag{15}$$

where

$$E_{\pi\,min}(E_\gamma) = E_\gamma + m_\pi^2 c^4 / 4E_\gamma . \tag{16}$$

Let us introduce Eq. (1) in (13) and then in (15) by taking into account Eq. (11):

$$F_{pH}^{\gamma}(E_\gamma, r, \theta, t) = B(r,\theta,t) \int_{E_{\pi\,\min}(E_\gamma)}^{\infty} \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} dE_\pi \times \int_{E_{k\,\min}(E_\pi)}^{\infty} N_{op}(E_k)\langle\varsigma\sigma_\pi(E_k)\rangle(t/t_m)^{-3/2} \times \exp\left(-3r^2 t_m / 2r_1^2 t\right) dE_k , \tag{17}$$

Where

$$B(r,\boldsymbol{\theta},t) = 3^{3/2} 2^{7/2} \boldsymbol{\pi}^{1/2} r_1^2 n_1(\boldsymbol{\theta},t) u_1(\boldsymbol{\theta},t) / r^2 u(r,\boldsymbol{\theta},t) \tag{18}$$

and t_m determined by Eq. (3) is the time at which the density of stellar FEP, at a distance of 1 AU, reaches the maximum value. The space distribution of gamma ray emissivity for different t/t_m will be determined mainly by function $r^{-2}(t/t_m)^{-3/2} exp\left(-3r^2 t_m / 2r_1^2 t\right)$, where t_m corresponds to some effective value of E_k in dependence of E_γ, according to Eq. (13) and (15). The biggest gamma ray emissivity is expected in the inner region $r \le r_i = r_1(2t/3t_m)^{1/2}$ where the level of emission $\propto r^{-2}(t/t_m)^{-3/2}$. Out of this region gamma ray emissivity decreases very quickly with *r* as $\propto r^{-2} exp\left(-(r/r_i)^2\right)$. For

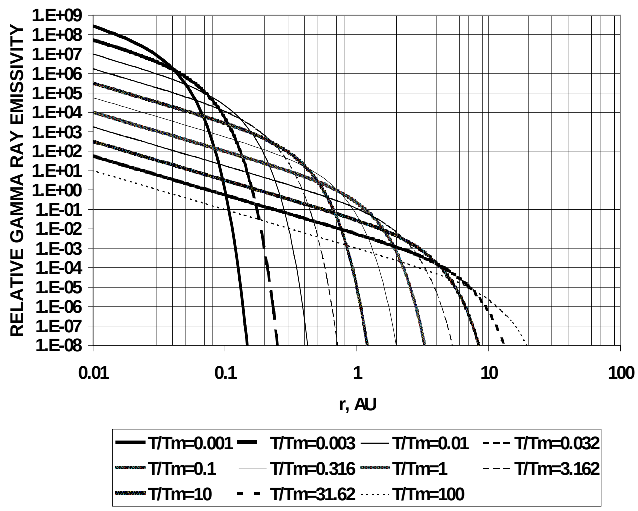

Fig. 2. Expected space distribution of gamma ray emissivity for different time T after stellar FEP generation in units of time maximum Tm on 1 AU, determined by Eq. (3). The curves are from T/Tm=0.001 up to T/Tm=100.

an stellar FEP event with total energy 10^{36}ergs at $t = t_m = 10^3$ sec, $r_i = 10^{13}$ cm, $n_1(\boldsymbol{\theta},t) \approx 500\, cm^{-3}$ $D_p(E_k) \approx 4 \times 10^{22}\, cm^2/sec$, we obtain

$$F^{\gamma}_{pp}\left(E_{\gamma} > 0.1\,GeV, r\right) \approx 10^{14} r^{-2}\,(t/t_m)^{-3/2} \times \exp\left(-3r^2 t_m \big/ 2r_1^2 t\right)\ photon.cm^{-3}\ sec^{-1} \qquad (19)$$

(on the distance $3\times10^{11}\,cm$ it gives 10^{-9} $ph.cm^{-3}s^{-1}$). Eq. (17) and (19) describe the space-time variations of gamma ray emissivity distribution from interaction of stellar energetic protons with stellar wind matter (see some examples in Figure 2).

5. Expected angle-time distribution of GR fluxes from stellar-sphere in periods of great FEP events

In the case of spherical symmetry for $r_{obs} > r_i$ we obtain

$$\Phi^{\gamma}_{pH}\left(E_{\gamma}, r_{obs}, \varphi, t\right) \approx F^{\gamma}_{pH}\left(E_{\gamma}, r = r_{obs}\sin\varphi, t\right) \times (\varphi_{max} - \varphi_{min})\, r_{obs}\sin\varphi, \qquad (20)$$

where φ is the angle between direction on the center of star and direction of observation,

$$\theta_{max/min} = \pm\arccos\left(r_{obs}\sin\varphi / r_i\right). \qquad (21)$$

6. Discussion and conclusions

Let us suppose that observer is on the distance $r_{obs} >> r_o$, where r_o is radius of stellar-sphere. In this case

$$\Phi^{\gamma}_{pH}\left(E_{\gamma}, r_{obs}, t\right) = 2\pi r_{obs}^{-2} \int_{-\pi/2}^{\pi/2} \cos\theta\, d\theta \int_0^{r_o} r^2 dr\, F^{\gamma}_{pH}\left(E_{\gamma}, r, \theta, t\right), \qquad (22)$$

where $F^{\gamma}_{pH}\left(E_{\gamma}, r, \theta, t\right)$ was determined by Eq. (17)-(19). For spherical-symmetrical modes of FEP propagation and stellar wind matter distribution, we obtain for GR flux

$$\Phi^{\gamma}_{pH}\left(E_{\gamma}, r_{obs}, t\right) = 4\pi r_{obs}^{-2} F^{\gamma}_{pH}\left(E_{\gamma}, r_1, t_m\right) \times (t/t_m)^{-1} r_1^3 \Phi\left(\frac{r_o}{r_1}(3t_m/t)^{1/2}\right)\ ph.cm^{-2}s^{-1}, \qquad (23)$$

where t_m was determined by Eq. (3) and $\Phi(x)$ is the probability function. For a flare star with total energy in FEP event 10^{36} ergs and $n_1(\theta, t) \approx 500\,cm^{-3}$ the expected emissivity at $t = t_m = 10^3$ sec will be determined by Eq. (19), and in this case Eq. (23) gives

$$\Phi^{\gamma}_{pH}\left(E_{\gamma} > 0.1GeV, r_{obs}, t\right) = 2\times10^{28} r_{obs}^{-2} \times (t/t_m)^{-1} \Phi\left(\frac{r_o}{r_1}(3t_m/t)^{1/2}\right) ph.cm^{-2}s^{-1}. \qquad (24)$$

According to Eq. (24) for $t_m = 10^3$ s at t =10 s and 100 s the value $\frac{r_o}{r_1}(3t_m/t)^{1/2} >> 1$ and $\Phi(x) \approx 1$, that at distance $r_{obs} = 3\times10^{18}\,cm \approx 1\,pc$ expected flux of GR with energy $E_{\gamma} > 0.1\ GeV$ will be 2×10^{-7} and 2×10^{-8} $ph.cm^{-2}s^{-1}$, correspondingly. Eq. (24) shows that the total flux of GR from stellar wind generated by FEP interaction with wind matter must fall inverse proportional with time. It is important for separation of GR generation in stellar wind from direct generation in stellar flare. I think that in near future important information can be obtained by GR monitoring of nearest stars with great FEP events (energy spectrum of FEP and parameters of propagation, stellar wind matter space-time distribution).

7. Acknowledgements

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